Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

UNIVERSITAT POLITÈCNICA DE CATALUNYA

BACHELOR'S THESIS

TITLE: Receiving and processing ADS-B signals for aircraft tracking

DEGREE: Bachelor's degree in Airport Engineering

AUTHOR: Xin Wang

DIRECTOR: Montoro López, Gabriel

DATE: 8th, July of 2019

ABSTRACT

Automatic Dependent Surveillance-Broadcast (ADS_B) system is one of the most important innovation of radar system which is used for direct state information exchange between aircraft.

The project consists of the study of ADS-B signal received from Barcelona airport. The low-cost device RTL-SDR is used to capture the signal and then be processed by Matlab. Through the Matlab demo execution such information can be extracted, per example, altitude, position, velocity, aircraft identification, etc. These information during the flight usually are displayed to cockpit, to enhance the situational awareness of pilot and its safety. Through the Simulink the spectrum of the ADS-B signal can be obtained and be studied. The capture of signal is taken in different places to see the influence the distance at the receiving signal process.

The present paper is organized as following structure: firstly, there is an overview of ADS-B system in the world. Second chapter talks about the background of the ADS-B system and deeper study of it. After it comes the study of the captured signal by RTL-SDR. The study of aerial traffic is followed the study of the signal. At the final part, the conclusion is reported.

RESUMEN

El sistema automático de transmisión de vigilancia dependiente (ADS_B) es una de las innovaciones más importantes del sistema de radar que se utiliza para el intercambio directo de información de estado entre aeronaves.

El proyecto consiste en el estudio de la señal ADS-B recibida desde el aeropuerto de Barcelona. El dispositivo de bajo costo RTL-SDR se utiliza para capturar la señal y luego ser procesado por Matlab. A través de la ejecución de la demo de Matlab, se puede extraer dicha información, por ejemplo, altitud,
posición, velocidad, identificación de la aeronave, etc. Esta información durante el vuelo generalmente se muestra a la cabina, para mejorar el conocimiento de la situación del piloto y su seguridad. A través de Simulink, se puede obtener y estudiar el espectro de la señal ADS-B. La captura de la señal se toma en diferentes lugares para ver la influencia de la distancia en el proceso de la recepción de señal.

El presente documento está organizado según la siguiente estructura: en primer lugar, se presenta una descripción general del sistema ADS-B en el mundo. El segundo capítulo habla sobre los antecedentes del sistema ADS-B y su estudio más profundo. Luego viene el estudio de la señal capturada por RTL-SDR. El estudio de tráfico aéreo con los datos obtenidos viene después del estudio de señal. Por lo último, la conclusión del trabajo.

INDEX

LIST OF FIGURE

LIST OF TABLE

CHAPTER 1. INTRODUCTION

1.1 OVERVIEW

With the unprecedented development in aviation field, the traditional radar surveillance is not enough to meet the need of air traffic control for both military and civil aviation. The conflict of demand for airspace resource and the shortage of available airspace resource is getting more and more severe, the new method of surveillance is needed.

Up to now, the ADS-B (Automatic Dependent Surveillance – Broadcast) is considered as safer and more-efficient replacement for radar in aviation industry. It is an airborne surveillance based on GPS and air-to-air, air-to-ground data link communication. Integrated with other technologies, maximizes the capacity of the ATC, and in especial, makes up for the deficiency in the radar systems at the airport.

Through the ADS-B technology can improve the pilot’s traffic situational awareness and the air safety. Comparing to the radar surveillance system, ADS-B can provide higher accuracy data, and faster data updating rate. The pilot can see the position of the adjacent aircraft and other information such as its flight intention, velocity, heading angle, and weather updates through the CDTI (Cockpit Display of Traffic Information), maintaining itself safety separation even reduces the separation distance. This shows that this kind of technology enables the possibility of the free flight and can reduce the work of ATC if pilot is aware of the nearby situation.

By using ADS-B system can realize real-time tracking to aircraft targets whether during the flight or on the ground, with this aircraft implements automatic monitoring and warning, avoids dangerous proximity and helps to reduce aircraft spacing. Thus, achieves to expand the flight capacity and increases utilization of airspace and airport. Meanwhile, enhances the management level of ATC to ensure the safety of flight.

As of today, most of the airlines have started to equip their fleet with ADS-B transponders in order to be ready when the technology becomes mandatory. In Europe, by the initial of June of 2020, the installation of ADS-B is mandatory so as in United States, by the initial of the 2020, wherever a Mode C transponder is currently required. (see [1])

1.2 AIM AND OBJECTIVE

The aim of this project is to study the ADS-B system, by using an RTL-SDR receiver which is able to receive ADS-B signals from Barcelona Airport between aircrafts-aircrafts and aircrafts-ground stations. The work consists of developing a software based on a demo provided by Matlab, for receiving and analyzing the signal and to check some aspect of aerial traffic.

1.3 METHODOLOGY

The Matlab software and RTL-SDR receiver are main instruments used during this project to achieve the objective.

The RTL-SDR with R820T2 tuner is setting up as an ADS-B air radar for best performance at 1090MHz, due to that it has the best sensitivity at this frequency. A vertically polarized antenna tuned to 1090 MHz is needed to receive signals. And the Matlab is the software chosen for listening and decoding ADS-B signal.

The work done is reported as the following description:

The first chapter is the introduction of the whole project which contains: an overview of the project and the aim and objective of the work.

The next chapter is a literature review of the ADS-B system which talk about the background of the ADS-B, its implementation, services, benefits, etc.

The following chapter is a study of the captured ADS-B signal, and its characteristic comparison in different places.

The penultimate chapter is an aerial traffic analysis based on the captured information.

The final chapter is a conclusion of the project.

CHAPTER 2. ADS-B SYSTEM OVERVIEW

2.1 BRIEF BACKGROUND AND HISTORY OF ADS-B SYSTEM

ADS-B is a new surveillance technology designed to help modernize the air transportation system. It provides foundational technology for improvement related to NextGen and SESAR. Both are similar projects that their aim is to transform the ATC system to support a larger volume of airplanes more efficiently.

Air traffic control (ATC) and radar were first used together in 1943 when Air Force air traffic controllers began using Ground Controlled Approach (GCA) equipment to help military pilots land safely in poor visibility. And two years later it was first time used in civil aviation at La Guardia Airport. Lately it is replaced by the Instrument Landing System (ILS) in the mid of 1950s. More transformations in radars were developed along with the increase of air traffic through the 1960s. Modern radars use Doppler effect to discriminate between moving and stationary targets to measure storm velocities. In the 1970s, the Air Traffic Control Radar Beacon System (ATCRBS), also known as Secondary Surveillance Radar (SSR), was upgrades to improve surveillance performance in dense airspace and transmissions between ground and aircraft. In the 1980s, the first air-to-air surveillance was developed, the airborne collision avoidance system (ACAS), which is required on all commercial aircraft operating in the U.S. and Europe. In the 1990s, radar surveillance of runways and taxiways was added. The next surveillance technology came after ACAS was the Traffic Collision Avoidance System, as its name says, it helps to detect potential airspace conflicts.

And most recently, ADS-B was developed to transmit aircraft position and velocity in 3 dimensions to other aircraft via an air-to-air datalink and to ground stations via an air-to-ground datalink. (see [2])

2.2 DEFINITION OF ADS-B

The ADS-B stands for Automatic Dependent Surveillance Broadcast:

- A (Automatic): do not need the artificial operation or external interrogation signal, it can automatically and periodically (at least once per second) transmit the information of position and velocity.

- D (Dependent): the proper functioning is related to the information transmission and the airborne equipment.

- S (Surveillance): surveillance aircraft position, altitude, velocity, heading, identification number and other information.

- B (Broadcast): Not specific to a user, the information of ADS-B is broadcasted to all aircrafts and ground station which has installed ADS-B receiver.

2.3 THEORY OF OPERATION

The main information of ADS-B is aircraft position information (longitude, latitude, altitude and the time), other additional information (conflict alerting information, pilot input information, path angle, turning point, etc.) and the aircraft information (identification number and category). Moreover, an information such as heading, airspeed, wind speed, wind direction and the external temperature is transmitted as well. This information can be obtained by the equipment as GNSS, INS, TRS, FMS and other airborne sensors (per example, the air data system).

The ADS-B system is divided in two parts: airborne and ground. The airborne equipment obtains the real-time position information of the aircraft and the velocity vector through the GNSS. By using the air data system obtains the information of pressure and altitude. And through the airborne transceiver broadcasting the previous mentioned information and other additional information such as aircraft identification code and category to the nearby aircraft and the ground stations, meanwhile, this aircraft will receive information of other aircrafts. So that, both ground and air planes are visible for all.

2.4 TYPES OF ADS-B SYSTEM

According to the transmission direction, there are two services type of ADS-B system: ADS-B OUT and ADS-B IN, which corresponds to transmitting signals and receiving signals respectively.

2.4.1 ADS-B OUT

The ADS-B OUT operates as a transmitter which broadcasts the aircraft information to other aircraft and ground stations via a digital datalink (1090 MHz) . The ADS-B signals travels line-of-sight from transmitter to receiver. ATC ground stations receive these signals for display of traffic to air traffic controllers. The aircrafts closers to the transmitting aircraft receive ADS-B signals, and then the lateral position (latitude and longitude), altitude, velocity, and flight number of the transmitting aircraft are displayed on a CTDI to the receiving aircraft pilot. It is mandatory when aircraft is operating in the airspace and currently requires the Mode C Transponder.

Generally, ADS-B OUT requires two pieces of equipment:

- A Mode-S Transponder (with Extended Squitter) or a Universal Access Transponder (UAT).
- A WAAS GPS or a GNSS/SBAS receiver.

To make it works properly the pairing of a UAT/Mode-S Transponder and WAAS GPS is needed.

2.4.2 ADS-B IN

The ADS-B IN operates as a receiver, not currently required. ADS-B IN receives ADS-B OUT signals from other transmitting aircrafts or signals from the ground stations providing pilot-usable flight information, such as advisory weather and traffic information to users.

ADS-B IN technology receives subscription-free advisory information broadcasts:

- FIS-B (FLIGHT INFORMATION SERVICE-BROADCAST): provides graphical weather and flight information obtained by using a 978 MHz UAT and ADS-B OUT transmission. They are only for advisory use for the purpose of assisting in long- and near-term planning and decision making.

- TIS-B (TRAFFIC INFORMATION SERVICE-BROAFCAST): supplements ADS-B air-to-air services to provide complete situational awareness in the cockpit of all traffic known to the ATC system. Even the aircraft hasn't installed the ADS-B equipment, or they use different frequencies between them, it is capable to broadcast information such as position, altitude to other aircrafts.

The maximum range between the transmitting aircrafts and the receiving aircrafts is greater than 100 nautical miles, allowing the CDTI to display traffic both near and far. (see[3])

2.5 CDTI

The CDTI is the most important human-machine surface of ADS-B system. It provides the navigation information, terrain warning message, meteorological radar information, traffic information service and the broadcasted message of nearby aircraft through the display system to pilot, offering him a more accuracy and precise air traffic information and the same window display of navigation information as air traffic controllers.

FIG. 2. 1COCKPIT DISPLAY OF TRAFFIC INFORMATION

2.6 ADS-B DATALINK

There are two ADS-B link frequency are widely used:

1. 978 MHz/UAT: transponders operate at 978 MHz using a larger bandwidth about 1.3 MHz and support both FIS-B and TIS-B services. To access FIS-B information, an aircraft must be equipped with a UAT/978 MHz receiver. FIS-B and TIS-B information can be shown on cockpit displays or portable electronic devices (PEDs) such as the iPad.

2. 1090MHz ES: 1090MHz transponders, known as “1090 ES” (“1090 MHz Extended Squitter”), with about 50 kHz of bandwidth. They send “Extended Squitter” messages, which include position, time and velocity. Aircraft equipped with 1090 ES transponders typically do not have access to ground-transmitted FIS-B services unless they also contain a UAT receiver.

Both they are not compatible with each other.

2.7 DEVELOPMENT AND USES CASES

The switch to a modern air traffic management system brought a lot of benefits. The most important one of these benefits is the cost, the traditional radar infrastructures are much more expensive to deploy and maintain compared to ADS-B. Futhermore, it provides significant operational enhancements for airlines and air traffic managers. The higher accuracy and precision improve safety and decrease the likelihood for air traffic incidents by a large margin. Therefore, pilots can profit from the enhanced situational awareness in their cockpit. In addition, it is less harmful effects on the environment.

ADS-B was developed to address some main use cases:

- Airport control:
    - Runway control/taxiing: due to its GPS-based localization the operation of handling of aircraft on the ground is improved where the very high precision is needed.

- Approach/take-off: improved accuracy increases ATC safety and make it possible to reduce the density of approaches and take-offs at busy airports, leading to significant cost reductions.

- En-route ATC:

  - Wide-area regions: ADS-B enables and significantly reduces cost for full en-route coverage of flights in very low-density regions such as the vast open spaces in Canada or Australia. Futhermore, it offers the opportunity to give a radar like control environment over oceanic, remote and geographically areas of the world, in areas with poor infrastructure as well as in areas, like Europe, rich of surveillance infrastructure.

  - Collision Avoidance: The TCAS is benefited from improved localization and reduces the danger of mid-air collision. Modern TCAS systems can utilize ADS-B messages to improve performance.

  - UAV Sense and Avoid: Control and collision avoidance for UAV is shifting to Sense and Avoid (SAA), permitting the UAV to self-separate from potential obstacle. (see [4])

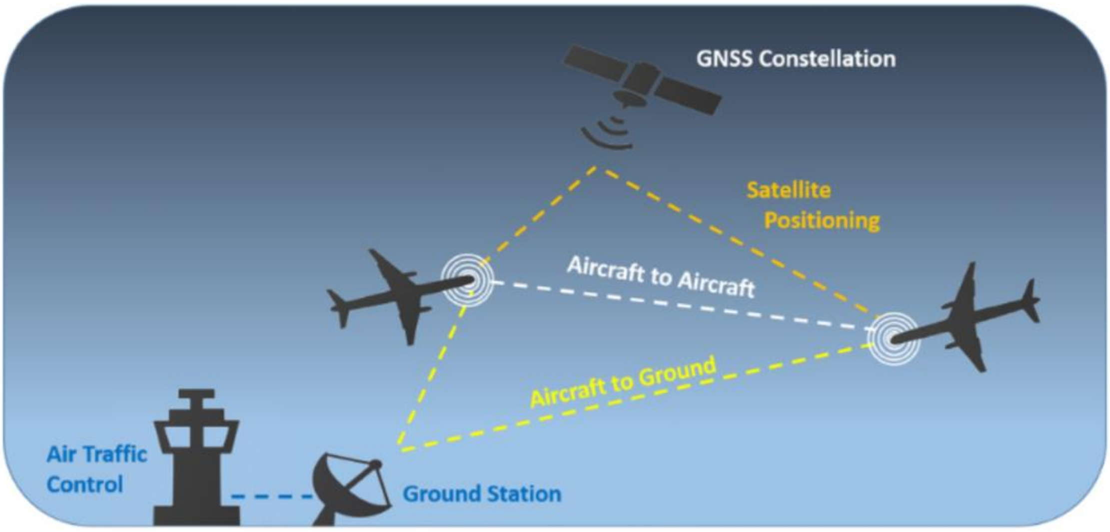


FIG. 2. 2 THE ADS-B ARCHITECTURE

2.8 ADS-B MESSAGE

In the worldwide, there are several available types of ADS-B data links, but the most common ones operate at 1090 MHz using the Mode-S signalling scheme.

Mode-S signalling scheme uses squitter messages, which are defined as a non-solicited messages used in aviation radio systems. There are two types of squitter message; shirt squitter (56 bits) and extended squitter (112 bits) which is used in ADS-B system. The content comes after focus on the extended squitter.

2.8.1 ADS-B MESSAGE CHARACTERS

The ADS-B message data block format uses PPM (Pulse Position Modulation) for transmitting the bits with the data rate of 1Mbit/s. PPM is a form of signal modulation where every bit comprises two chips, chip 1 and chip 2, every chip persists 0.5 µs. One high pulse (chip 1) followed by one low pulse (chip 2) presents the binary digit “1”, and whereas presents the binary digit “0”, so as it is shown the FIG. 2.3.

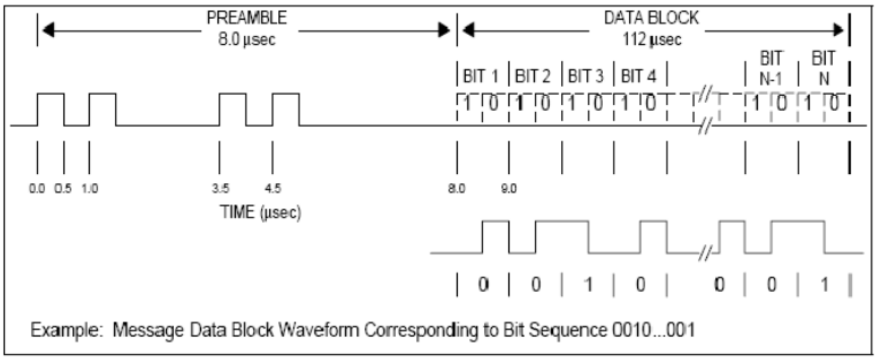


FIG. 2. 3 ADS-B MESSAGE WAVEFORM

2.8.2 ADS-B MESSAGE PREAMBLE

The message preamble includes 4 pulses, each pulses persists 0.5±0.05 µs. The intervals between the second, the third and the fourth pulse to the first transmission pulse are 1.0 µs, 3.5 µs and 4.5 µs.

2.8.3 ADS-B MESSAGE DATA PULSE

The ADS-B message data block starts after 8 µs from the first preamble pulse is received. Each ADS-B message has 112 µs of length, 1 µs for every bit. Each pulse must be located in the first half part or second part of the time slot. If two adjacent pulse located in two different time slots, the length of combined pulse must be 1.0±0.05 µs.

2.8.4 ADS-B MESSAGE PULSE FORM

The ADS-B message pulses are all square-wave pulses. In the same message, the height difference between any two pulses mustn't be bigger than 3 dB. The ascendant pulse time: 0.05 µs ≤ PulseRiseTime ≤ 0.1 µs, so as the descendent pulse time must reach the condition: : 0.05 µs ≤ PulseDecayTime ≤ 0.1 µs.

2.8.5 ADS-B MESSAGE STRUCTURE

The ADS-B message includes 4 pulses of preamble and 112 bits of extended squitter message.

The structure of the extended squitter message is following:

FIG. 2. 4 STRUCTURE OF ADS-B MESSAGE

The first 5 bits belong to DF field, if DF=17, it means that the message is broadcasted by Mode-S transponder; if DF=18 means that the message received is transmitted by non-Mode-S transponder, it could be ADS-B message or TIS-B message; DF=19 is reserved for military uses. In the case of project, the message received is DF=17 that means the following field is CA which corresponds to the bits from 6 to 8. The bit 9 to bit 32 in total 24 bits located in the ICAO address field. DATA contains the main information of ADS-B message where corresponds to bit 33 to 88, in total 56 bits. The last field is located 24 bits, from 89 to 112 which is called PARITY or Interrogator ID (PI).

TABLE 2. 1 STRUCTURE OF ADS-B MESSAGE

Num. Bits	Bits	Abbr.	Name
5	1 - 5	DF	Downlink Format
3	6 - 8	CA	Capability (additional identifier)
24	9 - 32	ICAO	ICAO aircraft address
56	33 – 88	DATA	Data
	(33 -37)	(TC)	Type Code
24	89 -112	PI	Parity/Interrogator ID

2.8.6 ADS-B MESSAGE FIELD DESCRIPTION

2.8.6.1 DF FIELD

Downlink Format (DF): ADS-B message start with DF=17 or 18 if it includes TIS-B message. They correspond to 10001 or 10010 in binary for the first 5 bits after the preamble.

2.8.6.2 CA FIELD

Capability(CA) is an additional identifier which its meaning varies with each ADS-B subtype.

2.8.6.3 ICAO FIELD

ICAO aircraft address (ICAO) is the unique transponder identification number for each aircraft.

2.8.6.4 DATA FIELD

Data (DATA) frame contains necessary data with the longitude of 56 bits. The first 5 bits of the DATA segment are Type Code of the message, indicated at bits 33-37. The three follow on bits are subtype code. In the Table 2.1 the information that each Type Code contains are shown.

TABLE 2. 2 ADS-B TYPE CODE AND CONTENT

Type Code	Content
1 – 4	Aircraft identification
5 – 8	Surface position
9 – 18	Airborne position (w/Baro altitude)
19	Airborne velocities
20 – 22	Airborne position (w/GNSS Height)
23 – 27	Reserved
28	Aircraft status
29	Target state and status information
31	Aircraft operations status

2.8.6.5 PARITY FIELD

PARITY/Interrogator ID (PI) is the last 24 bits serve to check if the message passed through a communication channel with no errors. ADS-B uses a cyclic redundancy check (CRC) to validate the correctness of the received message.

The CRC validation is based on the linear code theory. When the data is being transmitted, the system must order the transmitted binary data (set the sequence length to k bits), and according to a particular rule for generating one group of check code of length r. This group of check code will be added to the end of the message to generate a binary sequence of length n.

$$\boldsymbol{n = k + r} \tag{2. 1}$$

After the generation of binary sequence, this binary message will be sent by system.

This kind of encoding is known as a block code, the input data has the length of k, the check code, r, therefore the output data dimension is (n,k). Each block code has its own corresponding G(x), the CRC generator polynomial. The highest power is r. The check code of r bits is obtained through the calculation between polynomial G(x) and message data.

The process of generation of CRC code is as following:

The polynomial P(x) represents the transmitted message, shits the message to left r bits to obtain M(x), so that P(x)'s left will has a empty sequence of r length CRC code. By dividing the M(x) to polynomial G(x), the obtained reminder is the CRC code R(x).

$$R(x) = mod\left(\frac{M(x)}{G(x)}\right) \qquad (2.\,2)$$

Where mod represents modulo2 division.

If the transmitted code is S(x), so:

$$S(x) = x^{n-k}P(x) + R(x) = M(x) + R(x) \qquad (2.\,3)$$

The ADS-B system based on the Mode-S, its downlink data uses an improved polynomial (112, 88) CRC code (eq. 2.4) to detect any error which its length is smaller or equal to n-k=24.

$$G(x) = x^{24} + x^{23} + x^{22} + x^{21} + x^{20} + x^{19} + x^{18} + x^{17} + x^{16} + x^{15} + x^{14} + x^{13} + x^{12} + x^{10} + x^{12} + x^{3} + 1 \qquad (2.\,4)$$

2.9 ADS-B MESSAGE INFORMATION

2.9.1 ADS-B AIRBORNE POSITION

The airborne position information includes the information of longitude and latitude, due to that is real-time (maximum error ≤200 μs) position information, the time information is needed to determine the target position.

The Type Code field of must be one of these numbers: 0, 9 to 18, 20 to 22. The Subtype Code indicates the surveillance status, the alerting message of aircraft, and also add the NIC field to aircraft status report to complete the NIC encoding, with the purpose to indicate the accuracy of navigation, such as if it contains the altitude information, either the altitude information comes from GNSS is geometric height information or barometric altitude information. The latitude and longitude is coded with CPR format. The message of airborne position information is shown on the Table.

TABLE 2. 3 AIRBORNE POSITION FRAME

AIRBORNE POSITION INFORMATION		
MSG Bits	**Abbr.**	**Content**
1 - 5	TC	Type Code
6 - 7	SS	Surveillance Status
8	NICsb	NIC supplement - B
9 - 20	ALT	Altitude
21	T	Time
22	F	CPR odd/even frame flag
23 - 39	LAT-CPR	Latitude in CPR format
40 - 56	LON-CPR	Longitude in CPR format

2.9.1.1 Altitude

The format of altitude code is12 bits length, which occupies the bits from 9 to 20. The bit 16 (bit 48 in ADS-B frame) indicates the unit for altitude, and it is called as Q bit. When Q=0, means that the altitude is encoded in multiple of 100 foot, the bit 9 to bit 15 and bit 17 to 20 correspond to C1, A1, C2, A2, C4, A4, B1, B2, D2, B4, D4, respectively. When Q=1, the increment unit is 25 foot. In this case, the binary coding is used, the MSB is bit 9. The value of altitude can be represented from -1000 inches to 50175 foot.

An example of calculation of altitude is like following:

```
1100001 1 1000
        ^
      Q-bit
```

FIG. 2. 5 Q-BIT IN ALTITUDE FRAME

In this case, the Q=1, the increment step is 25 foot. First, remove the Q-bit, which leaves 11000011000 or 1560 in decimal. The final altitude would be:

$$Altitude = N \times 25 - 1000 = 38000\, ft. \tag{2.1}$$

2.9.1.2 Time

The time information is included in the bit 21, which indicates if the horizontal position data is synchronized with UTC. When T=1, represents synchronized, if it is T=0, unsynchronized.

2.9.1.3 CPR format

The CPR format (F) situated in the bit 22, it serves to indicate under CPR format coding if the frame of information of longitude and latitude is even or odd. When F=1, means is odd, F=0, even.

For example, the two following messages are received:

```
8D40621D58C382D690C8AC2863A7
8D40621D58C386435CC412692AD6

|    | ICAO24 |      DATA      |  CRC   |
|----|--------|----------------|--------|
| 8D | 40621D | 58C382D690C8AC | 2863A7 |
| 8D | 40621D | 58C386435CC412 | 692AD6 |
```

FIG. 2. 6 RECEIVED MESSAGES

The DATA field in binary format would be following:

```
| DATA                                                                           |
|================================================================================|
| TC    | ... | ALT          | T | F | CPR-LAT           | CPR-LON           |
|-------|-----|--------------|---|---|-------------------|-------------------|
| 01011 | 000 | 110000111000 | 0 | 0 | 10110101101001000 | 01100100010101100 |
| 01011 | 000 | 110000111000 | 0 | 1 | 10010000110101110 | 01100010000010010 |
```

FIG. 2. 7 RECEIVED DATA IN BINARY FORMAT

In both messages we can find DF =17 and TC=11, with the same ICAO24 address 40621D. These two frames are valid for decoding the position of the aircraft. Assume the first message is the newest message received. The CPR representation of coordinates is as in Fig.2.8.

```
| F | CPR Latitude      | CPR Longitude     |
|---|-------------------|-------------------|
| 0 | 10110101101001000 | 01100100010101100 |   -> newest
| 1 | 10010000110101110 | 01100010000010010 |
|---|-------------------|-------------------|

In decimal:

|---|-------------------|-------------------|
| 0 | 93000             | 51372             |
| 1 | 74158             | 50194             |
|---|-------------------|-------------------|

CPR_LAT_EVEN: 93000 / 131072 -> 0.7095
CPR_LON_EVEN: 51372 / 131072 -> 0.3919
CPR_LAT_ODD:  74158 / 131072 -> 0.5658
CPR_LON_ODD:  50194 / 131072 -> 0.3829
```

FIG. 2. 8 CPR REPRESENTATION OF COORDINATES

2.9.1.4.1 Since CPR latitude and longitude are encoded in 17 bits, 131072 (2^{17}) is the maximum value.

2.9.1.4 Latitude and longitude

ADS-B equipment broadcasts latitude and longitude information obtained by GNSS to let users know the localization information of aircraft. The motion orbit of aircraft or ground vehicles must be continuously, so inside the latitude and longitude frame the change of MSB is very slowly. In the most extreme cases, sometimes, after the end of the flight, the MSB of latitude and longitude frame remains unchanged. If every time it broadcasts the complete latitude and longitude information is a big waste for limited transmission bandwidth because of the ADS-B message update rate, and the position information is the most frequent information broadcasted.

Based on the CPR representation of coordinates, the MSB is being ignored. The ignoration of MSB causes that multiple position corresponding to the same group of code, and if only one message is received, after decoding it is still uncertain of the transmitter's specific location. To solve this problem, CPR format coding can be broadcasted in even or odd format. Both are transmitted with 50% of probability, if they are received in short time (10 s for airborne position and 50 s for ground position), the aircraft position can be easily determined. Once the receiver get the specific position, i.e., the MSB is determined, the subsequent single message, whether it is odd or even, the position of aircraft or ground vehicle can be estimated.

There are exceptions, if receiver knows it self's previous position, so the odd/even message is not needed to decode to estimate the position of aircrafts or ground vehicles. Because the position information carried by the single message must be corresponding to an integral multiple of 360 miles of North-South or East-West, as ADS-B's receiving range can not be bigger than 180 miles, the position which is closer to ADS-B receiver is the true location.

As mentioned before, there are two ways to decode an airborne position based on these messages:

- Unknown position, using both types of messages (aka globally unambiguous position).
- Knowing previous position, using only one message (aka locally unambiguous position).

The number of latitude zone is defined as NZ =15. This value divides the range of airborne decoding range (360 miles), i.e., the same code is corresponding to the different position. The ground position has ignored the bit-19, the two higher order bits, so the available ground position range is 90 miles.

The functions that used for the calculation are:

- floor (x): rounds each element of X to the nearest integer less than or equal to that element.

- mod(x,y): fins the modulus after division.

$$\boldsymbol{mod(x,y) = x - y \times floor\left(\frac{x}{y}\right)\ when\ y \neq 0} \qquad \textbf{(2. 2)}$$

For the following CPR calculation the value of Y is always positive. When x is positive, mod(x,y) is equal to the modulus of x divides y. When x is a negative angle, mod (x,y) is the modulus of (x+360º) divided by y.

The longitude function of latitude x is NL(x). The function domain is as following:

$$\boldsymbol{NL(lat) = \begin{cases} 59 & lat = 0^0 \\ 1 & lat > 87^0 \\ 1 & lat < -87^0 \\ 2 & lat = 87^0 \\ 2 & lat = -87^0 \\ floor\left\{2\pi\left[arcos\left(1 - \frac{1-\cos\left(\frac{\pi}{2\times NZ}\right)}{cos^2\left(|lat|\times\frac{\pi}{180^0}\right)}\right)\right]\right\} & others \end{cases}} \qquad \textbf{(2. 3)}$$

The amount of computation of NL(lat) by encoding is huge, to simplify, the table of annex 1 can be used. The latitude of the table is obtained by following equation:

$$\boldsymbol{lat = \frac{180^0}{\pi} arcos\left(\sqrt{\frac{1-cos\frac{\pi}{2\times NZ}}{1-cos\frac{2\pi}{NL}}}\right)\ when\ NL = 2\ to\ 4NZ - 1} \qquad \textbf{(2. 4)}$$

During the decoding process, the subscript i is used to differ even format (i=0) from odd format (i=1).

2.9.1.4.1 Globally unambiguous position (decoding with two messages)

The time interval between two message (even and odd) can not be more than 10 seconds due to the maximum distance to airborne target is 3 miles. If the target velocity is 1850 km/h (1000 mph) within 10 s, it can fly 5.1km (2.8 miles).

ADS-B receiver by receiving even format position message (XZ_0, YZ_0) and odd format position message (XZ_1, YZ_1) can determine the target's position Rlat and Rlon.

Step 1: Calculate beforehand $Dlat_i$ (the size of north and south latitudes) when i=0 and i=1, respectively.

$$\boldsymbol{Dlat_i = \frac{360^0}{4 \times NZ - i} \begin{cases} \frac{360^0}{60} \\ \frac{360^0}{59} \end{cases}} \qquad \textbf{(2. 5)}$$

Step 1: Calculate the latitude index j

$$\boldsymbol{lat_{cprEven} = \frac{YZ_0}{2^{Nb}},\ lat_{cprOdd} = \frac{YZ_1}{2^{Nb}} \qquad where\ \ Nb = 17} \qquad \textbf{(2. 6)}$$

$$\boldsymbol{j = floor\left(59 \times lat_{cprEven} - 60 \times lat_{cprOdd} + \frac{1}{2}\right)} \qquad \textbf{(2. 7)}$$

Step 3: Calculate the value of latitude Rlat when i=0 and i=1.

$$\boldsymbol{Rlat_i = Dlat_i \cdot \left[mod(j, 60 - i) + lat_{cpri}\right]} \qquad \textbf{(2. 8)}$$

For the southern hemisphere, values will fall from 270 to 360 degrees. To make sure the latitude is within the range [-90, +90]:

$$Rlat_i = Rlat_i - 360 \quad if\ Rlat_i \geq 270 \tag{2. 9}$$

If the value of NL($Rlat_0$) and NL($Rlat_1$) are not the same, that means there is latitude span, the receiver must keep waiting until there are two CPR format message with no latitude span.

Step 4: if NL($Rlat_0$) and NL($Rlat_1$) are same, according to the latest airborne position CPR format message even or odd, calculate $Dlon_i$.

$$N_i = \max(1, NL \cdot Rlat_i - i) \tag{2. 10}$$

$$Dlon_i = \frac{360^0}{N_i} \tag{2. 11}$$

Step 5: Calculate the longitude index m

$$NL = NL(Rlat_i) \tag{2. 12}$$

$$lon_{cprEven} = \frac{XZ_0}{2^{Nb}}, \quad lon_{cprOdd} = \frac{XZ_1}{2^{Nb}} \tag{2. 13}$$

$$m = floor\left[lon_{cprEven}(NL - 1) - lon_{cprOdd} \cdot NL + \frac{1}{2}\right] \tag{2. 14}$$

Step 6: Depending on the parity of last received CPR format message, determine the longitude value $Rlon_1$ or $Rlon_0$.

$$Rlon_i = Dlon_i\left[mod(m, N_i) + lon_{cpri}\right] \qquad (2.15)$$

2.9.1.4.2 Locally unambiguous position (decoding with one message)

This method allows us to calculate the position of aircraft with one message knowing a reference position. Assume that lon and lat message comes from GNSS, the corresponding CPR format message are lon_{cpri} and lat_{cpri}.

Step 1: Calculate north-south latitude span $Dlat_i$ by using the equation 2.5.

Step 2: Calculate the latitude index j

$$j = floor\left(\frac{lat}{Dlat_i}\right) + floor\left(\frac{mod(lat, Dlat_i)}{Dlat_i} - lat_{cpri} + \frac{1}{2}\right) \qquad (2.16)$$

Step 3: Calculate latitude

$$Rlat_i = Dlat_i \cdot (j + lat_{cpri}) \qquad (2.17)$$

Step 4: Calculate $Dlon_i$

For even message:

$$Dlon_0 = \begin{cases} \frac{360^0}{NL(lat)}, & if\ NL(lat) > 0 \\ 360, & if\ NL(lat) = 0 \end{cases} \qquad (2.18)$$

For odd message:

$$Dlon_1 = \begin{cases} \frac{360^0}{NL(lat)-1}, \ if\ NL(lat) - 1 > 0 \\ 360, \ if\ NL(lat) - 1 = 0 \end{cases} \quad \textbf{(2. 19)}$$

Step 4: Calculate longitude index m

$$m = floor\left(\frac{lon}{Dlon_i}\right) + floor\left[\frac{mod(lon, Dlon_i)}{Dlon_i} - lon_{cpri} + \frac{1}{2}\right] \quad \textbf{(2. 20)}$$

Step 5: Calculate longitude

$$Rlon_i = Dlon_i \cdot (m + lon_{cpri}) \quad \textbf{(2. 21)}$$

2.9.2 ADS-B GROUND POSITION

The ground position information includes the information such as longitude, latitude, aircraft and ground vehicles' status, heading and track angle, except the altitude. Due to that it is real-time information, the time is needed as well as airborne position information.

The Type Code of ground position frame must be 5, 6, 7 o 8, each one represents different navigation accuracy, so as radius tolerance. The ground position information comprises the velocity and track angle of aircraft and ground vehicles. In addition, the information of longitude and latitude. The longitude and latitude information uses CPR format code.

TABLE 2. 4 GROUND POSITION FRAME

GROUND POSITION INFORMATION		
MSG Bits	**Abbr.**	**Content**
1 - 5	TC	Type Code
6 - 12	MS	Move Status
13	F-hdg	Heading/track angle flag
14 - 20	Hdg	Heading/Track angle
21	T	Time
22	F	CPR odd/even frame flag
23 - 39	LAT-CPR	Latitude in CPR format
40 - 56	LON-CPR	Longitude in CPR format

The move status has the length of 7 bits, located from the bit 6 to bit 12. It uses nonlinear coding which means that different encoding range uses different code unit. The bigger is the code value, the bigger is the value of unit, which means the area of movement for aircrafts and vehicles is bigger.

The bit 13 is an indicator for the following 7 bits if the information contained is valid. ‘’1’’ means true, ‘’0’’ means false.

The bit 14 to bit 20 uses to stock the orientation information of aircrafts and vehicles. The due north is 0º, encoding in clockwise direction, the code unit is 2.8125º.

Other information is the same as mentioned in 2.9.1.2, 2.9.1.3 and 2.9.1.4.

2.9.3 AIRCRAFT IDENTIFICATION

An aircraft identification information includes the emitter category (EC), and characters (C) for aircraft identification. This kind of message has DF=17 or 18, and TC is from 1 to 4 which correspond to the emitter category D, C, B, A. The data field is configured as following table:

TABLE 2. 5 AIRCRAFT IDENTIFICATION FRAME

MSG BIT	1-5	6-8	9-14	15-20	21-26	27-32	33-48	39-44	45-50	51-56
CONTENT	TC	EC	C1	C2	C3	C4	C5	C6	C7	C8

The combination of EC value and TC value determines the category of the aircraft such as if it is heavy, large, small, light, glider, etc.. If EC=0 that means this information is not available.

The character code table used for mapping number to characters is defined as:

#ABCDEFGHIJKLMNOPQRSTUVWXYZ#####_###############0123456789###### where the # is not used, and _ represents a separation. The representation of each character and their decimal are:

- A – Z: 1 – 26
- 0 – 9: 48 – 57
- _: 32

```
CharacterCode = ...
  ' ABCDEFGHIJKLMNOPQRSTUVWXYZ                     0123456789      '
```

FIG. 2. 9LOOKUP TABLE IN MATLAB CODE

For example, the message 8D4840D6202CC371C32E0576098 is received. The structure of the message is following:

TABLE 2. 6 AIRCRAFT ID MESSAGE DECODING

	DF	CA	ICAO	DATA			PI
HEX	8	D	4840D6	2	0	2CC371C32CE0	576098
BIN	10001	101	******	00100	000	************	******
DEC	17	5		4	0		
				TC	*		

In the table 2.6 it is seen that DF=17 and TC=4 which confirms that this is an aircraft identification message. Then an aircraft callsign can be decoded.

TABLE 2. 7 DECODED MESSAGE

HEX	20	2CC371C32CE0							
BIN	00100000	001011	001100	001101	110001	110000	110010	110011	100000
DEC		11	12	13	49	48	50	51	32
LTR		K	L	M	1	0	2	3	_

KLM1023 is the decoded aircraft callsign.

2.9.4 ADS-B AIRBORNE VELOCITY

There are two types of airborne velocity message, determined by 3-bit subtype in the message. With subtype 1 and 2, surface velocity (ground speed) is reported. And in subtype 3 and 4, aircraft airspeed is reported. The message contained information is explained in the table 2.8 and table 2.9 for each type.

Type 2 and 4 are for supersonic aircraft and type 1 and 3 for subsonic aircraft. Unless there is any commercial supersonic aircraft flying around, it is rare to see any of those types (2 and 4). The most common ones are with subtype 1.

An aircraft velocity message has DF =17 or DF =18, and TC=19, the subtype codes are represented in bits 38 to 40.

3.1 Subtype 1 (Ground speed)

The subtype 1 (subsonic, ground speed), are broadcast when ground velocity information is available.

The intent change flag (IC) indicates the flight intent (descending or turning) whether changed, if IC=1, changes.

The reserved-A indicates if the aircraft possesses instrument flight capability. When RESV_A=1, represents that it is equipped with A1 or higher level of ADS-B equipment.

The velocity uncertainty range is between 0 to 4. When NAC=0, the accuracy is highest, HFOMR<0.3m/s, VFORM<0.46m/s. When NAC=4, the accuracy is worst, HFOMR>10m/s, VFOMR>15.24m/s.

TABLE 2. 8 AIRBORNE VELOCITY SUBTYPE 1 MESSAGE BITS EXPLAINED

c	DATA BITS	LEN	ABBR	CONTENT
33 – 37	1 – 5	5	TC	Type code
38 – 40	6 – 8	3	ST	Subtype
41	9	1	IC	Intent change flag
42	10	1	RESV_A	Reserved-A
43 – 45	11 – 13	3	NAC	Velocity uncertainty
46	14	1	S_ew	East-West velocity sign
47 – 56	15 - 24	10	V_ew	East-West velocity
57	25	1	S_ns	North-South velocity sign
58 – 67	26 – 35	10	V_ns	North-South velocity
68	36	1	VrSrc	Vertical rate source
69	37	1	S_vr	Vertical rate sign
70 – 78	38 - 46	9	Vr	Vertical rate
79 – 80	47 – 48	2	RESV_B	Reserved-B
81	49	1	S_Dif	Diff from baro alt, sign
82 – 88	50 – 56	7	Dif	Diff from baro alt

The east-west velocity sign indicates the direction of velocity is go to east or west. If its value is 0 indicates east, otherwise, west.

the east-west velocity's bits are used to report the horizontal velocity of aircraft. When the subtype=1, means subsonic, the unit is mile/hour. When it is 0 represents that there is no information about velocity, if it is 1, means the velocity is 0 mph, if it is 1022 means the velocity is 1021 mph, and so on. The maximum value 1023 represents the velocity is higher than 1021.5 mph. When the subtype is 2, so as supersonic, the unit is 4 mph, '0' means no information contained, '1' means the velocity is zero mph, '1022' represents 4084 mph and so on. The maximum value '1023' indicates that the velocity is higher than 4086 mph.

The north-south velocity sign and velocity has the same meaning as the east-west velocity sign and velocity. The value '0' indicates North.

The vertical rate source indicates the source of the vertical rate information, the value ‘0’ represents that the information comes from GNSS, otherwise, from atmospheric pressure.

The vertical rate sign indicates if the aircraft is climbing or descending, the value ‘0’ indicates climbing.

The vertical rate is not related to the subtype, the unit is always 64 foot per minute. The value ‘0’ represents there is no information contained, ‘1’ the velocity is 0., ‘510’ the velocity is 32576 foot per minute, and so on. The maximum value ‘511’ represents that the vertical rate is higher than 32608 ft/min.

The difference from barometric altitude sign indicates if GNSS altitude is bigger than atmospheric altitude. ‘0’ represents bigger and ‘1’, smaller.

The difference from barometric altitude reports the value of difference. The unit is 25 foot. ‘0’ means that there is no GNSS altitude available, so the value of difference can not be obtained. ‘1’ represents that the difference is 0 feet, ‘2’ , 25 foot, and so on. The maximum value ‘127’ represents that the difference is bigger than 3137.5 foot.

3.2 Subtype 3 (Air speed)

Subtype 3 indicates that it is subsonic aircraft, the airspeed is broadcasted when ground speed information is not available, while airspeed is available.

TABLE 2. 9 AIRBORNE VELOCITY SUBTYPE 3 MESSAGE BITS EXPLAINED

c	DATA BITS	LEN	ABBR	CONTENT
33 – 37	1 – 5	5	TC	Type code
38 – 40	6 – 8	3	ST	Subtype
41	9	1	IC	Intent change flag
42	10	1	RESV_A	Reserved-A
43 – 45	11 – 13	3	NAC	Velocity uncertainty
46	14	1	S_hdg	Heading status
47 – 56	15 - 24	10	Hdg	Heading (proportion)
57	25	1	AS-t	Airspeed Type
58 – 67	26 – 35	10	AS	Airspeed
68	36	1	VrSrc	Vertical rate source
69	37	1	S_vr	Vertical rate sign
70 – 78	38 - 46	9	Vr	Vertical rate
79 – 80	47 – 48	2	RESV_B	Reserved-B
81	49	1	S_Dif	Diff from baro alt, sign
82 – 88	50 – 56	7	Dif	Diff from baro alt

The information contained in the airborne velocity type 3 message are similar to the type 1, except following content:

- Heading status (S-hdg): indicates whether the heading data is usable or not, ‘0’ means no, and ‘1’ means usable.

- Heading (Hdg): represents the proportion of the degrees of a full circle, i.e. 360 degrees.

$$heading = \frac{Decimal(Hdg)}{1024} * 360^0 \qquad (2.\ 22)$$

- Airspeed type (AS-t): this field indicates if the airspeed is indicated airspeed (IAS) or true airspeed (TAS). If it is ‘0’ indicates IAS and ‘1’ TAS.

- Airspeed (AS): these 10 bits are used to report the velocity of the aircraft. The representation of each value is the same as other velocity fields.

CHAPTER 3 STUDY OF ADS-B SIGNAL

In this chapter, the ADS-B signal is studied by using RTL-SDR dongle and MATLAB. The RTL-SDR will receive the ADS-B signal of the airport of Barcelona and decoding it to obtain the information of aircrafts. The obtained information will be used later for the study of air traffic situation.

3.1 RTL-SDR

RTL-SDR is a very cheap ~$25 USB dongle that can be used as a computer based radio scanner for receiving live radio signals in our area (no internet required). Depending on the particular model it could receive frequencies from 500kHz up to 1.75 GHz. Besides being used as ADS-B radar, it can be applied to use as police radio scanner, decode unencrypted digital voice transmissions, etc. (see [5])

FIG. 3. 1RTL-SDR R820T2 NOOELEC

3.2 MATLAB SIMULINK MODEL

The Simulink model for receiving signals of ADS-B is designed based on the RTL-SDR receiver model provided by Communication Toolbox Support Package for RTL-SDR radio of MATLAB.

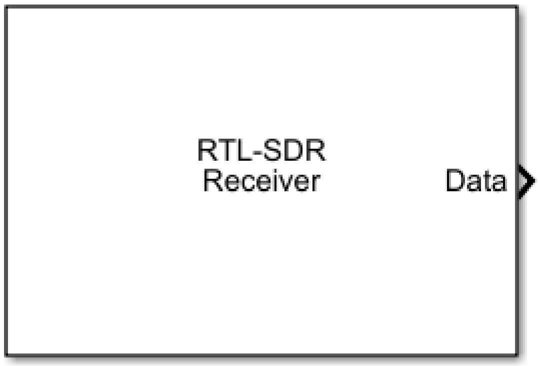


FIG. 3. 2 SIMULINK MODEL RTL-SDR RECEIVER

The value of receiver is already set by default if the ADSBExample is used.

```
sigSrc = comm.SDRRTLReceiver(userInput.RadioAddress,...
  'CenterFrequency',1090e6,...
  'EnableTunerAGC',false,...
  'TunerGain',60,...
  'SampleRate',frontEndSampleRate,...
  'OutputDataType','single',...
  'FrequencyCorrection',0);
```

FIG. 3. 3 MATLAB CODE FOR RTL-SDR CONFIGURATION

Once the ADSBExample is executed, the following information is needed to enter:

1. Reception duration in second.

2. Signal source: it could be captured data or RTL-SDR radio or ADALM-PLUTO radio.

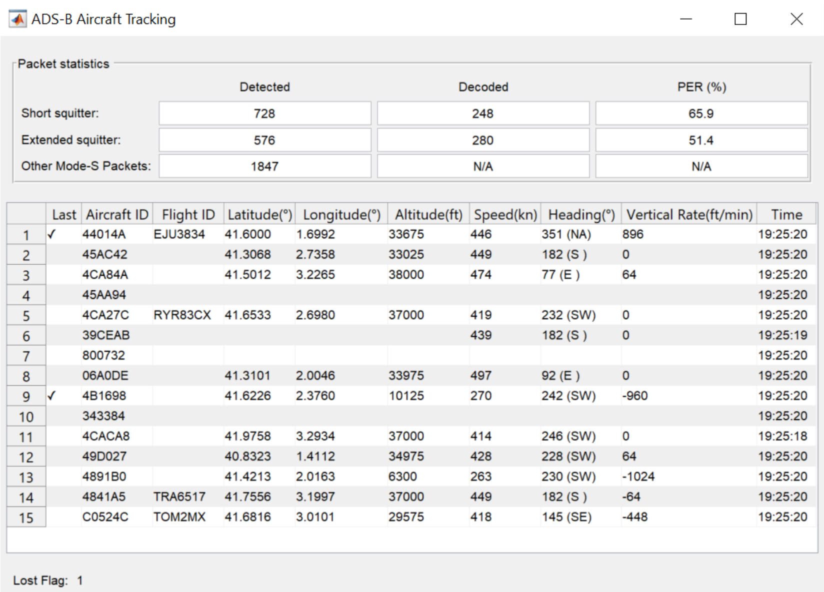
3. Optional output methods (map and/or text file)

After introduced required data, there are two windows appeared: one displays the aircraft decoded information, and another one is a map which shows shows the movement of detected aircarafts.

3.3 ANALYSIS OF INFORMATION DECODED BY MATLAB

The distance between the Bellvitge and the Barcelona airport El Prat is almost 6.9 km which is acceptable for our antenna to receive the ADS-B signal though the effective ranges of an ADS-B signal is much bigger but it depends also on antenna height, aircraft altitude and terrain.

After executed the ADSBExample the following figures are showed. The Fig.3.3 shows the decoded information of the ADS-B message in real-time. As it shows, this demo code allows users to observe the real-time airspace situation, the contained information such as aircraft ID, flight ID, latitude, longitude, altitude, speed, heading, vertical rate.


ADS-B Aircraft Tracking

Packet statistics

	Detected	Decoded	PER (%)
Short squitter:	728	248	65.9
Extended squitter:	576	280	51.4
Other Mode-S Packets:	1847	N/A	N/A

	Last	Aircraft ID	Flight ID	Latitude(°)	Longitude(°)	Altitude(ft)	Speed(kn)	Heading(°)	Vertical Rate(ft/min)	Time
1	✓	44014A	EJU3834	41.6000	1.6992	33675	446	351 (NA)	896	19:25:20
2		45AC42		41.3068	2.7358	33025	449	182 (S)	0	19:25:20
3		4CA84A		41.5012	3.2265	38000	474	77 (E)	64	19:25:20
4		45AA94								19:25:20
5		4CA27C	RYR83CX	41.6533	2.6980	37000	419	232 (SW)	0	19:25:20
6		39CEAB					439	182 (S)	0	19:25:19
7		800732								19:25:20
8		06A0DE		41.3101	2.0046	33975	497	92 (E)	0	19:25:20
9	✓	4B1698		41.6226	2.3760	10125	270	242 (SW)	-960	19:25:20
10		343384								19:25:20
11		4CACA8		41.9758	3.2934	37000	414	246 (SW)	0	19:25:18
12		49D027		40.8323	1.4112	34975	428	228 (SW)	64	19:25:20
13		4891B0		41.4213	2.0163	6300	263	230 (SW)	-1024	19:25:20
14		4841A5	TRA6517	41.7556	3.1997	37000	449	182 (S)	-64	19:25:20
15		C0524C	TOM2MX	41.6816	3.0101	29575	418	145 (SE)	-448	19:25:20

Lost Flag: 1

FIG. 3. 4 ADS-B SCREEN

FIG. 3. 5 CAPTURED AIRCRAFTS IN BARCELONA AIRSPACE

The most received message is from non-Mode-S transponder which is not decoded by the Matlab program. The extended squitter and short squitter messages are from Mode-S transponder and they are possible to be decoded. After several times of test that is showed the PER% (packet error rate) of short squitter is always higher than extended squitter. The PER% value for extended message is maintained close to 50%.

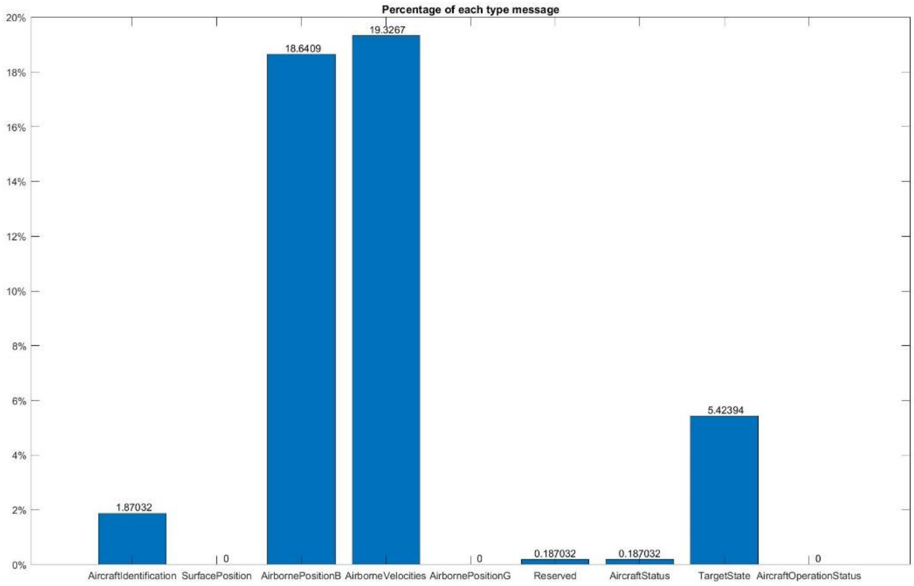


FIG. 3. 6 PERCENTAGE OF EACH TYPE MESSAGE

As shown in the figure 3.6 [see Annex 2], the message of airborne velocities and the airborne position are most broadcasted by aircraft, due to the purpose of conflict detection and self-separation to enhance the safety and efficiency.

3.4 SIGNAL DECODING PROCESS BY MATLAB

Once user introduced the desired simulation time and the source of signal, the simulation can start (also it asks whether user wants to launch the map and to log decoded information to the file).

The first of all is to calculate the ADS-B system parameters based on the user input. After obtained the ADS-B system parameters, the received message can be parsed by using *helperAdsbRxMsgParser.m* where the physical layer packets are parsed and the aircraft information is extracted.

The function *helperAdsbRxPhy.m* demodulates short and extended squitter ADS-B packet in the received signal. The synchronized Mode-S packet samples are searched during the process by using *helperAdsRxPhySync.m* function and then extract the Mode-S header information and raw data bits by using *helperAdsRxPhyBitParser.m* function.

The function *helperAdsRxPhyBitParser.m* demodulates the synchronized Mode-S packets found previously. It demodulates samples into data bits, parses the packet and finally check the CRC. If the packet is not a downlink format type 17

(DF=17) or type 11 acquisition squitter, the packet is discarded. CRC check value is 0 means it is correct otherwise failed.

3.5 ADS-B SIGNAL ANALYSIS

3.5.1 CAPTURE OF SIGNAL

To analyze the same signal, the captured signal can be saved. The additional tool Save RTL-SDR Data offered by (see [6]) made it possible.

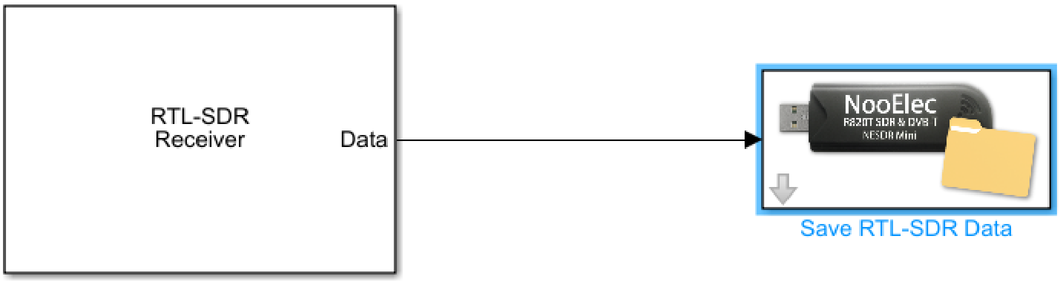


FIG. 3. 7 SAVE RTL-SDR DATA SIMULINK MODEL

Once captured signal is saved, the Import RTL-SDR Data tool can be used to extract the signal information afterwards.

FIG. 3. 8 IMPORT RTL-SDR DATA TOOL

3.5.2 PULSE POSITION MODULATION

As mentioned before the ADS-B system uses PPM for transmitting information.

Pulse-position modulation (PPM) is a form of signal modulation in which M message bits are encoded by transmitting a single pulse in one of 2^M possible required time shifts. (see [7] and [8])

This is repeated every T seconds, such that the transmitted bit rate is M/T bits per second. It is primarily useful for optical communication systems, when tend to have little or no multipath interference. (see [9])

In modulated signal (PPM), the amplitude and width of pulses are constant while the position of pulses varies proportionally with the amplitude of analogical useful signal. Carrier signal is from a clock. (see [10])

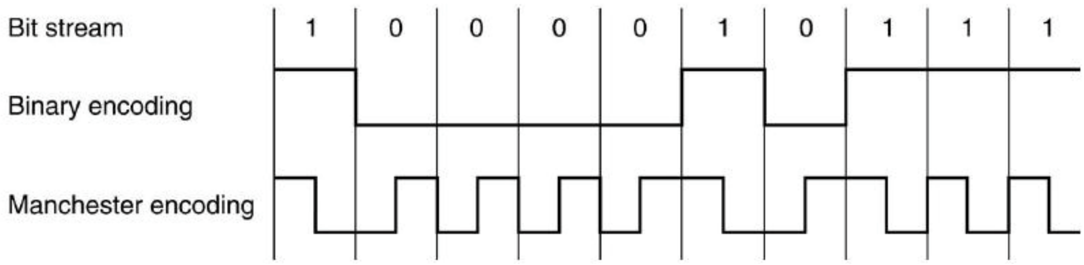


FIG. 3. 9 MANCHESTER ENCODING

The encoding of PPM of ADS-B signal is same as Manchester encoding, the data of each pulse is occupying either the first of second half of the entire pulse, such as showed in the Fig.3.8.

3.5.3 FREQUENCY DOMAIN ANALYSIS

Signals can be viewed and analyzed in the frequency domain as well as the time domain, which makes the understanding of the content of frequency much easier.

Spectrum Analyzer of Simulink shows the spectrum of the received signal, and has bandwidth of f_s MHz. This means that it shows spectral activity is in the range:

$$\left(f_c - \frac{f_s}{2}\right) to \left(f_c - \frac{f_s}{2}\right) Hz \tag{3. 1}$$

centered around f_c, the center frequency of the RTL-SDR. (see [6])

In this case, the center frequency is 1090 MHz and configured it's sampling rate to 2.4 MHz, which means that signals in the range 1088.6 MHz to 1091.4 MHz would be captured, downconverted and complex demodulated by the device.

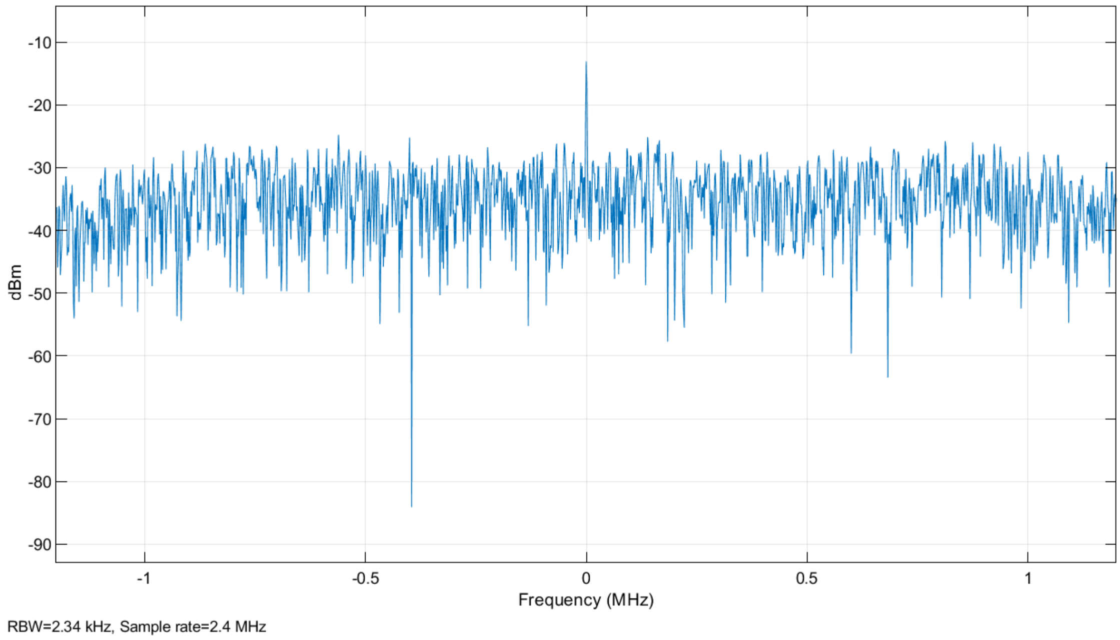


FIG. 3. 10 SPECTRUM OF CAPTURED SIGNAL

The Fig.3.10 shows a typical ADS-B spectrum centered in the frequency 1090 MHz where the signal power at the center frequency is major. With the measurement tools of analyzer is possible to get exact number of interested data, such as the peak value is -13.0797 dBm in the center frequency.

3.5.4 TIME DOMAIN ANALYSIS

The received signal after treated by RTL-SDR returns a complex value of signal, but it is only analytic representation to facilitate the mathematic operations.

The signal in the time domain plot it is observed that it has sinusoidal form and if zoom it in (Figure 3.14), the carrier signal is in rectangular form, so as what it supposed has to be as it is transmitted in PPM. In the Figure 3.12 is plotted both the real part and the imaginary part of the signal. It is difficult here to distinct pulse shape because the noises interference. The pulse shape is needed to see better the characteristics of signal.

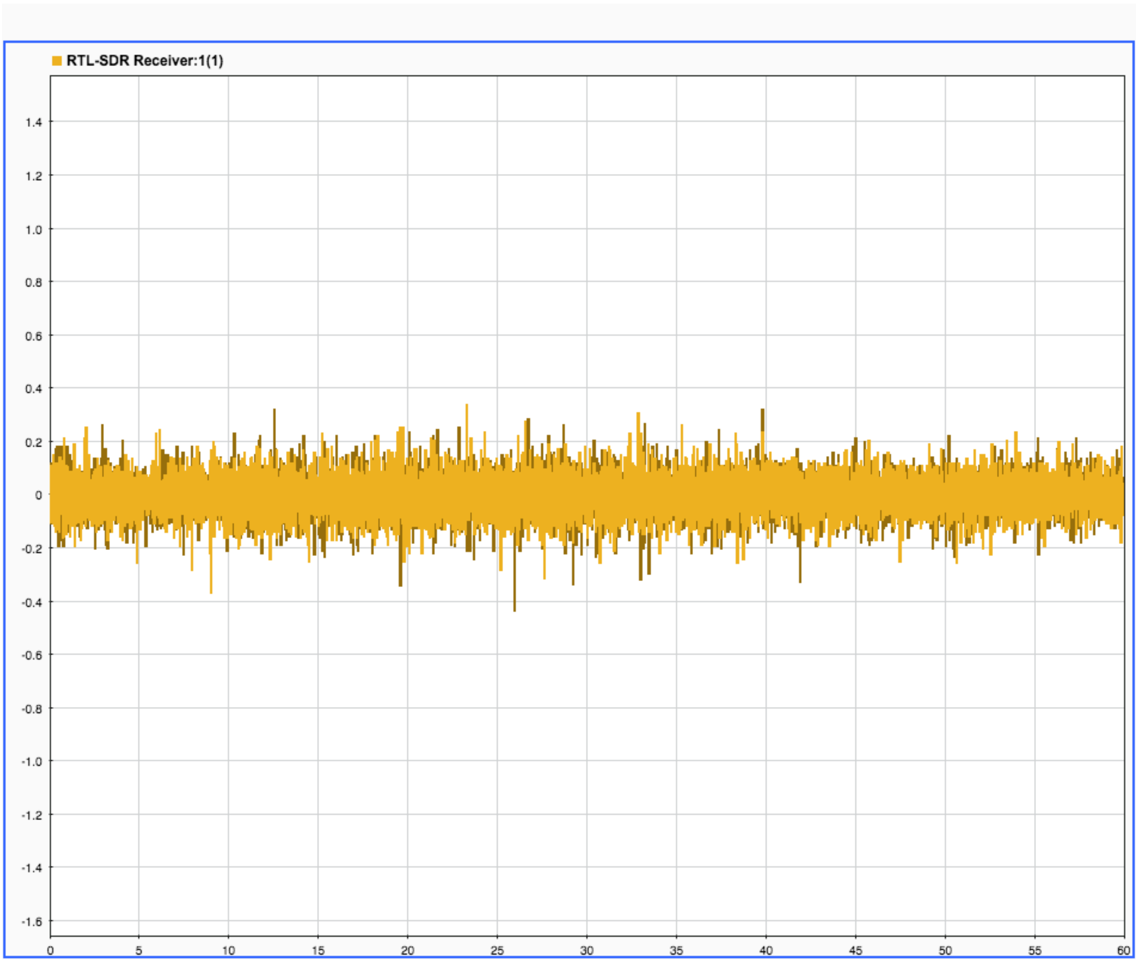


FIG. 3. 11 TIME DOMAIN COMPLEX SIGNAL

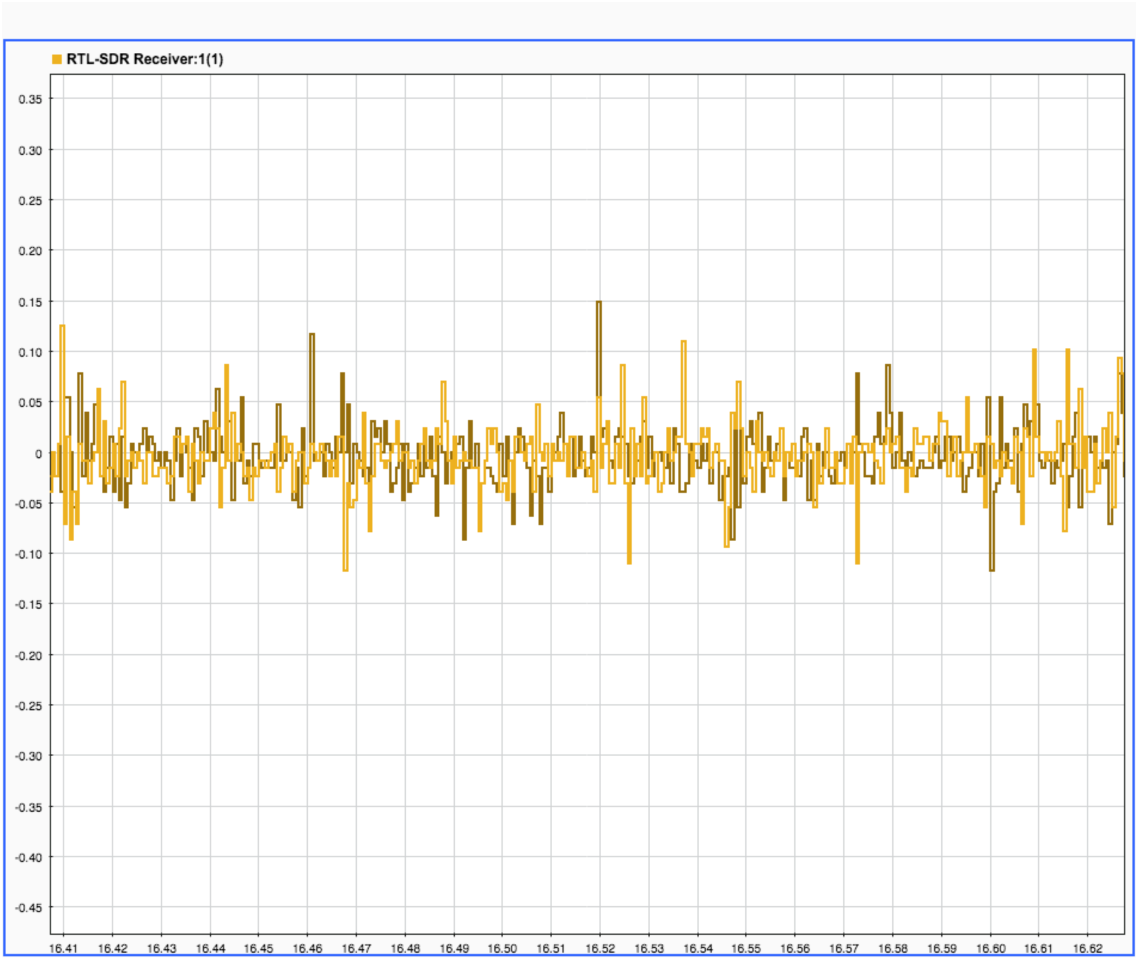


FIG. 3. 12 TIME DOMAIN SIGNAL ZOOMED IN

3.5.5 PPM SIGNAL IQ SAMPLES

The received signal has two parts: a real part and a imaginary part which are called as I and Q samples. The figure 3.12 shows the oscillation of one captured frame.

It is observed that there is a kind of frequency offset exists in the signal, because either the transmitter system or receiver system is real, imperfect hardware. The major part of transmitters used on the aircraft are old, containing imprecise clock oscillators.

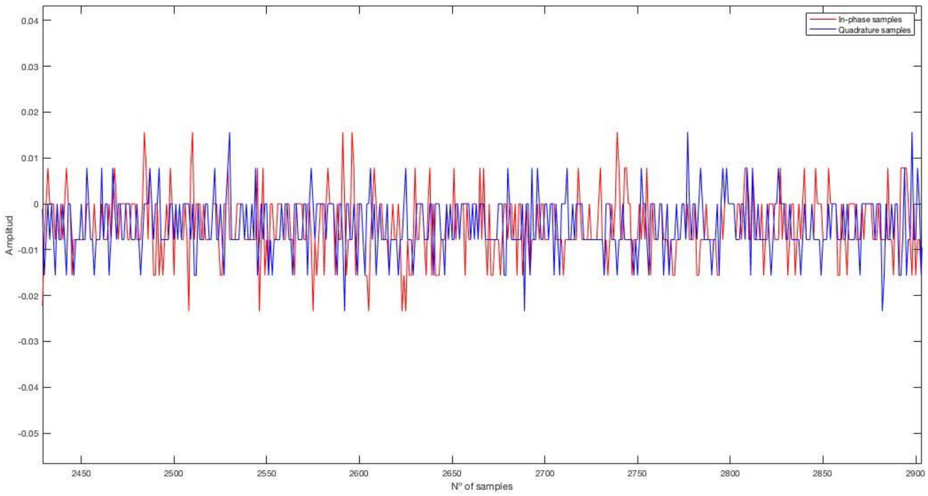


FIG. 3. 13 IQ SAMPLES

3.5.6 PULSE SHAPING

The main role of pulse shaping filter is in conjunction with other filters in the processing chain to limit the bandwidth of the signal. The pulse shape used in this project is Raised Cosine (RC), it is one of the most popular pulse shapes.

The signal form in Figure 3.14 is a signal received with raised cosine filter. The code is based on the ADSBExample code of Matlab (see Annex 3). By comparing it with the signal of Figure 3.12, it is observed that the original signal has a sinusoidal form and after the filtering, the form of signal is close to the PPM, but there are still some interference or noises.

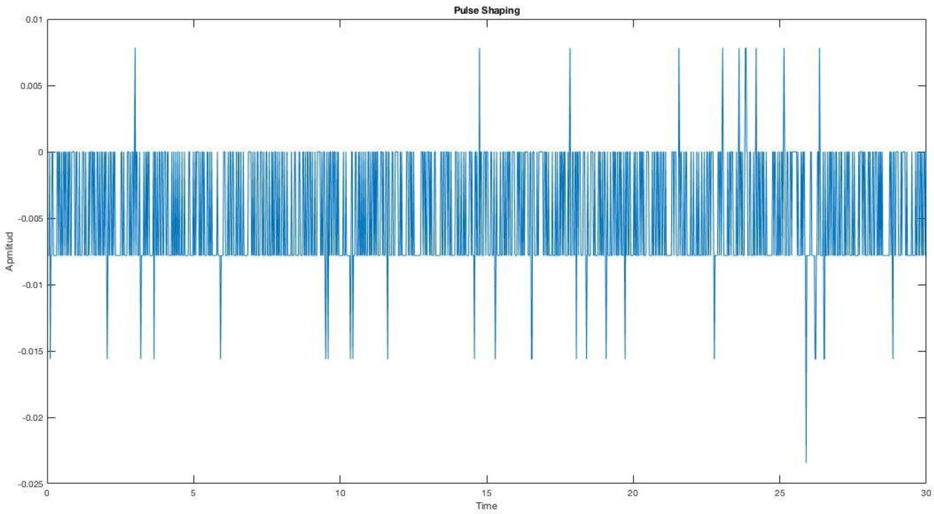


FIG. 3. 14 ADS-B SIGNAL AFTER PULSE SHAPING

3.6 Comparison of signal spectrum captured in different place

The test of capture of signal is taken in four places different to see if the factor as distance has an influence in the quality of signal. In the table 3.1 shows the location selected and the distance from it to airport.

TABLE 3. 1 DISTANCE FROM AIRPORT TO SELECTED PLACES

PLACE	DISTANCE TO AIRPORT (km)
El Prat	2.8
La Farga	7.2
La Pubilla Cases	8.5
El Guinardó	16

To compare, two variables are used, the peak value of the spectrum and the SNR value of the signal.

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{3. 2}$$

$$SNR_{dB} = 10log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) \quad (3.3)$$

The peak value of spectrum and SNR vale of the signal for each place is showed in the table 3.2:

TABLE 3. 2 CHARACTERISTIC VALUE

Place	Peak value (dBm)	SNR (dBc)
El Prat	-14.1451	-18.36
La Farga	-13.0797	-19.21
La Pubilla Cases	-13.5607	-18.57
El Guinardó	-13.506	-19.27

According to the equation 3.4 and 3.5 the quality of signal must be declined due to the longer distance of transmission, but in this case as the table 3.2 shows the peak value and SNR value have not got a big difference between them. This result is due to the receiver dongle cannot be set to receive a specific signal from a specific transmitter, it receives any signal of the set frequency which is nearby. Therefore, the peak value and the SNR does not change a lot.

$$FSPL(d) = \frac{4\pi df^2}{c} \quad (3.4)$$

$$FSPL(dB) = 10log_{10}\left(\left(\frac{4\pi df}{c}\right)^2\right) \quad (3.5)$$

Where c is the light speed, $3x10^8$m/s, and f is the carrier frequency 1090 MHz, both are constant.

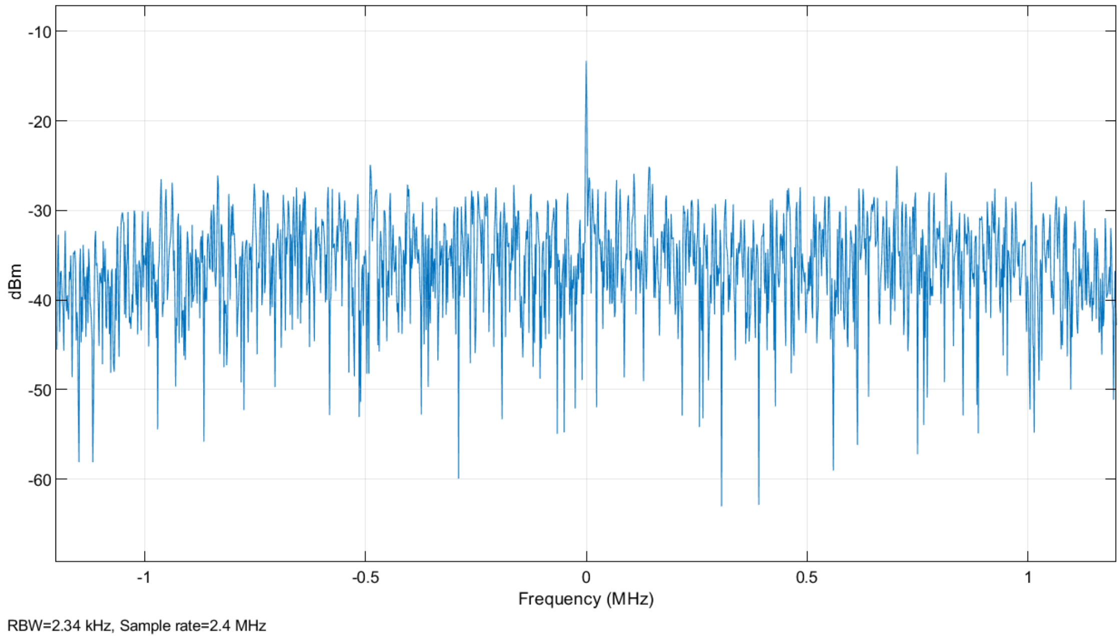


FIG. 3. 15 SPECTRUM OF CAPTURED SIGNAL IN PUBILLA CASES

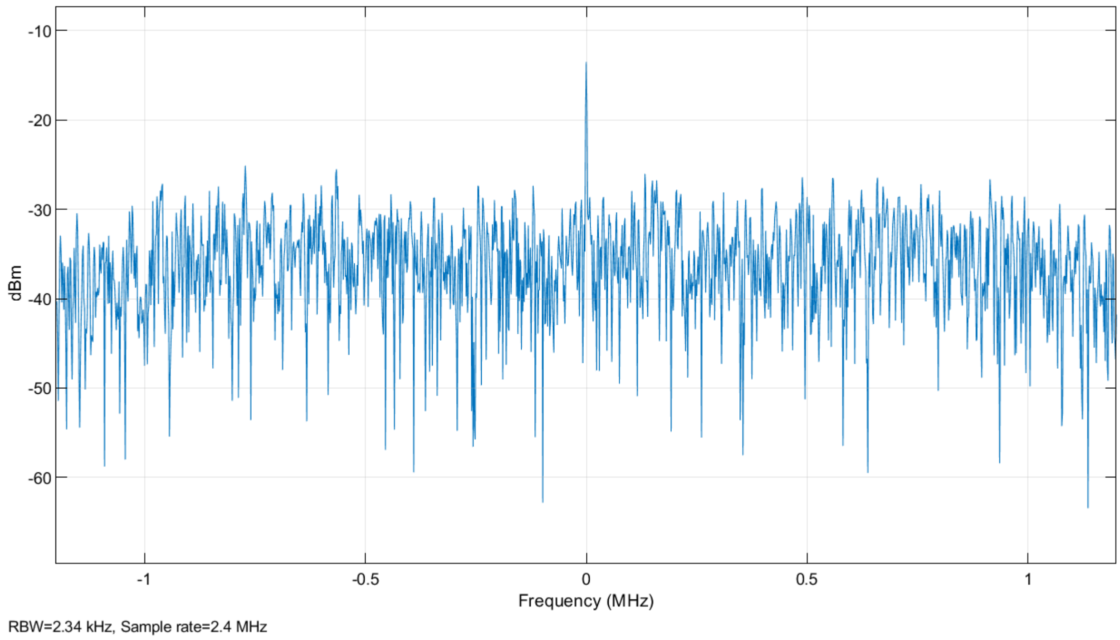


FIG. 3. 16 SPECTRUM OF CAPTURED SIGNAL IN EL GUINARDÓ

CHAPTER 4 ANALYSIS OF AERIAL TRAFFIC

The ADS-B messages provide users a big amount of information with the purpose to enhance the situational awareness of pilot and increase the efficiency in the airport.

The aircrafts broadcast its state information with high frequency to ease the work of controllers. The benefit of implement of ADS-B system is huge and with its information users can determine a lot of things, the density of airspace, the possible collision between aircrafts, etc.

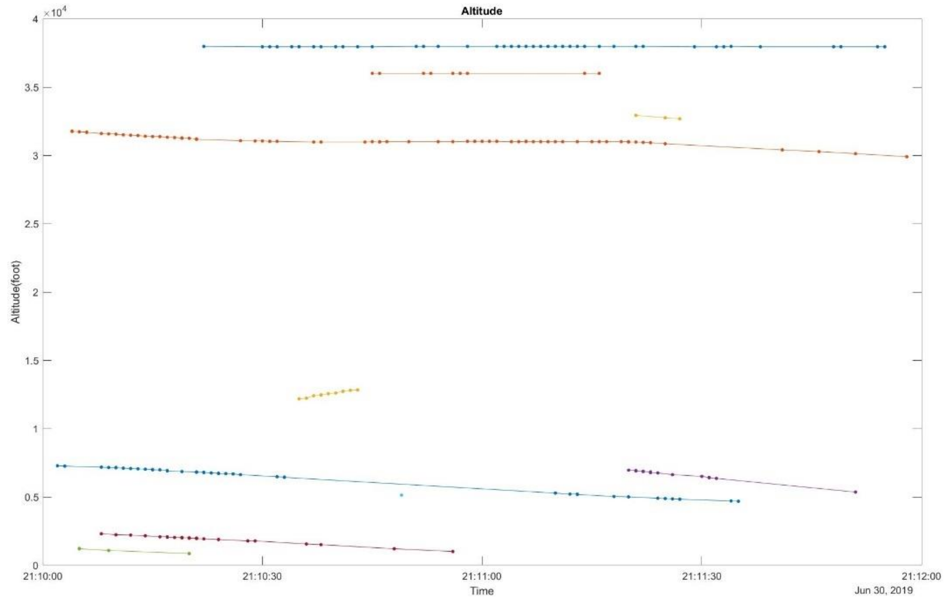


FIG. 4. 1 ALTITUDE PROFILE

The figure 4.1 shows the altitude profile of detected message. There are 9 aircrafts detected, 4 of them are upper than 30000 foot, which means they are not going to land at moment. Another four aircrafts are below 1000 foot and its graphic shows that they are descending. The unique one which is between both range of altitude, there is not enough information to determine what it is going to do, but according the evolution of the segment, it seems it is ascending.

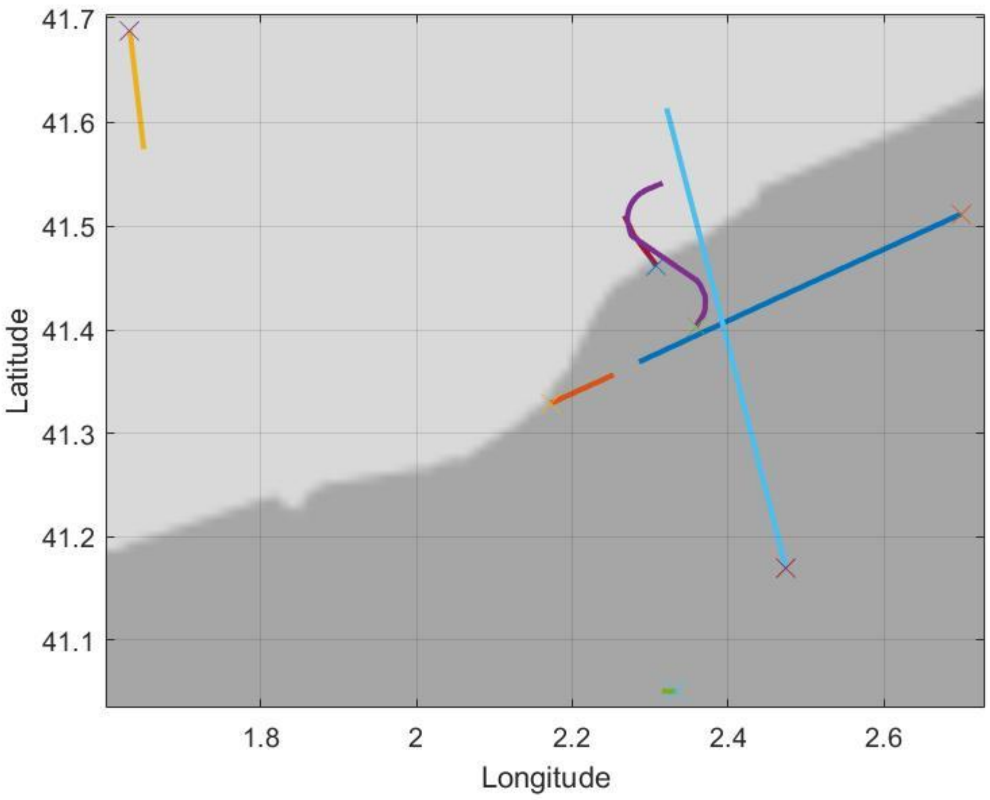


FIG. 4. 2 AIRCRAFT ROUTE DIRECTION

With obtained information it is also possible to see the route direction of captured airplane, users through the map can see how these aircrafts are distributed in the air.

This is only a simple example of what users can do with the obtained information. Obviously there are more usage of these information.

CHAPTER 5 CONCLUSION

During this project, the RTL-SDR dongle by setting its variables to desired value the real-time air traffic tracking has been possible. All intentions of flight of each aircraft can be received by the dongle and then be decoded. The simulation shows that not all received signals are come from the Mode-S transponder, there are other transponders which use 1090 MHz to transmit information. The packet error rate (PER) is higher in short squatter (DF=11) than extended squitter (DF=17 o 18). After processing the ADS-B signal such information are extracted, altitude, airborne position and velocity of the aircraft, which improves the situational awareness of plot, less work for air controllers and the most important they are key information for the detection of conflict.

The captured signal analysis is as following: First one part is the study of its spectrum distribution. The peak value of spectrum is situated in the center, due to that ADS-B signal is only be transmitted and received in this range of frequency, so the activity in the frequency 1090Mhz is highest. Second part is its distribution of signal along time axis. ADS-B signal is a complex signal which uses PPM to transmit the data, its signal has a sinusoidal form. After it, the constellation distribution shows that either the real part or imaginary part of signal has a symmetric aspect along the time and the is has a frequency offset ude to the old equipment. The signal after the RC filter has less interference or noise, and its form is closer to PPM, every pulse has some amplitude.

After processed the ADS-B signal the extracted information such as altitude, latitude, longitude, velocities could be used to analyze the air traffic situation. In the project a simple analysis through decoded altitude information is done. The altitude profile tells to users how many aircrafts are en route, and how many are descending to approach. Besides this, other information could be extract such as conflict detection.

BIBLIOGRAPHY

[1] ttps://www.ads-binfo.com/

[2] http://adsbforgeneralaviation.com/a-brief-history-of-ads-b/

[3] William R. Richards, Kathren O'Brien, and Dean C. Miller, ''Next air traffic surveillance technology'', *www.boeing .com/commercial/aeromagazine* (2010)

[4] Martín Strohmeier, Matthias Schafer, Vincent Lenders and Ivan Martinovic,''Realities and challenges of nextgen air traffic management: the case of ADS-B'', *IEEE Communications Magazine* (Volume:52, Issue:5, May 2014)

[5] https://www.rtl-sdr.com/about-rtl-sdr/

[6] Bob Stewart, Kenneth Barlee, Dale Atkinson and Louise Crockett, *Software_Defined_Radio_using_MATLAB_Simulink_and_the_RTL-SDR___book_and_support_files,* Strathdyde Academic Media, Glasgow, Scotland, Uk (2017)

[7] K. T. Wong. "Narrowband PPM Semi-Blind Spatial-Rake Receiver & Co-Channel Interference Suppression" (PDF). *European Transactions on Telecommunications*. The Hong Kong Polytechnic University. **18** (2): 193–197. doi:10.1002/ett.1147 (March 2007).

[8] Yuichiro Fujiwara. "Self-synchronizing pulse position modulation with error tolerance". *IEEE Transactions on Information Theory*. 59: 5352–5362. arXiv:1301.3369. doi:10.1109/TIT.2013.2262094. (2013)

[9] https://en.wikipedia.org/wiki/Pulse-position_modulation

[10] https://www.ijeat.org/wp-content/uploads/papers/v7i2/B5251127217.pdf

Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

UNIVERSITAT POLITÈCNICA DE CATALUNYA

ANNEXOS

TITLE: Receiving and processing ADS-B signals for aircraft tracking

DEGREE: Bachelor's degree in Airport Engineering

AUTHOR: Xin Wang

DIRECTOR: Montoro López, Gabriel

DATE: 8th, July of 2019

ANNEX 1

TABLE OF LATITUDE CORRESPODING NL

Abs|Lat 度|	NL	Abs|Lat 度|	NL	Abs|Lat 度|	NL
(87, 90]	1	(69. 4424, 70. 4545]	21	(45. 5463, 46. 8673]	41
87	2	(68. 4232, 69. 4424]	22	(44. 1945, 45. 5463]	42
(86. 5354, 87]	3	(67. 3965, 68. 4232]	23	(42. 8091, 44. 1945]	43
(85. 7554, 86. 5354]	4	(66. 3617, 67. 3965]	24	(41. 3865, 42. 8091]	44
(84. 8917, 85. 7554]	5	(65. 3185, 66. 3617]	25	(39. 9226, 41. 3865]	45
(83. 9917, 84. 8917]	6	(64. 2662, 65. 3185]	26	(38. 4124, 39. 9226]	46
(83. 0720, 83. 9917]	7	(63. 2043, 64. 2662]	27	(36. 8503, 38. 4124]	47
(82. 1396, 83. 0720]	8	(61. 0492, 62. 1322]	28	(35. 2290, 36. 8503]	48
(81. 1980, 82. 1396]	9	(59. 9546, 61. 0492]	29	(33. 5399, 35. 2290]	49
(80. 2492, 81. 1980]	10	(58. 8476, 59. 9546]	30	(31. 7721, 33. 5399]	50
(79. 2943, 80. 2492]	11	(57. 7275, 58. 8476]	31	(29. 9114, 31. 7721]	51
(78. 3337, 79. 2943]	12	(56. 5932, 57. 7275]	32	(27. 9390, 29. 9114]	52
(77. 3679, 78. 3337]	13	(55. 4438, 56. 5932]	33	(25. 8292, 27. 9390]	53
(76. 3968, 77. 3679]	14	(54. 2782, 55. 4438]	34	(23. 5450, 25. 8292]	54
(75. 4206, 76. 3968]	15	(53. 0952, 54. 2782]	35	(21. 0294, 23. 5450]	55
(74. 4389, 75. 4206]	16	(51. 8934, 53. 0952]	36	(18. 1863, 21. 0294]	56
(73. 4518, 74. 4389]	17	(50. 6715, 51. 8934]	37	(14. 8282, 18. 1863]	57
(72. 4588, 73. 4518]	18	(49. 4278, 50. 6715]	38	(10. 4705, 14. 8282]	58
(71. 4599, 72. 4588]	19	(48. 1604, 49. 4278]	39	[0, 10. 4705]	59
(70. 4545, 71. 4599]	20	(46. 8673, 48. 1604]	40		

ANNEX 2

Matlab code to read data:

```
%%The log file has to be loaded previouly

%Percentatge of each type message

shortSquitterposition=[];
extendedSquitterposition=[];
Othersposition=[];
i=1;
e=1;
s=1;
o=1;
while(i<=length(seal2.Message))
   if(seal2.DF(i)==17)
      extendedSquitterposition(e)=i;
      e=e+1;
   else
      if(seal2.DF(i)==11)
         shortSquitterposition(s)=i;
         s=s+1;
      else
         Othersposition(o)=i;
         o=o+1;
      end
   end
   i=i+1;
end
T_exSquitter=seal2(extendedSquitterposition,:);
T_shortSquitter=seal2(shortSquitterposition,:);
T_noModeS=seal2(Othersposition,:);
%Eliminate rows without information from extende squitter table and clasify
%its information accorfing to the captured flight
i=1;
b=1;
A=1;
AircraftIdentification=[];
S=1;
SurfacePosition=[];
P=1;
AirbornePositionBaro=[];
V=1;
AirborneVelocities=[];
G=1;
AirbornePositionGNSS=[];
R=1;
Reserved=[];
```

```
T=1;
AircraftStatus=[];
Q=1;
TargetState=[];
U=1;
AircraftOperationStatus=[];

for i=1:length(T_exSquitter.Message)
   if(T_exSquitter.TC(i)==0)
      blankposition(b)=i;
      b=b+1;
   else
      if (T_exSquitter.TC(i)>=1&&T_exSquitter.TC(i)<=4)
         AircraftIdentification(A)=i;
         A=A+1;
      else
         if(T_exSquitter.TC(i)>=5&&T_exSquitter.TC(i)<=8)
            SurfacePosition(S)=i;
            S=S+1;
         else
            if(T_exSquitter.TC(i)>=9&&T_exSquitter.TC(i)<=18)
               AirbornePositionBaro(P)=i;
               P=P+1;
            else
               if(T_exSquitter.TC(i)==19)
                  AirborneVelocities(V)=i;
                  V=V+1;
               else
                  if(T_exSquitter.TC(i)>=20&&T_exSquitter.TC(i)<=22)
                     AirbornePositionGNSS(G)=i;
                     G=G+1;
                  else
                     if(T_exSquitter.TC(i)>=23&&T_exSquitter.TC(i)<=27)
                        Reserved(R)=i;
                        R=R+1;
                     else
                        if(T_exSquitter.TC(i)==28)
                           AircraftStatus(T)=i;
                           T=T+1;
                        else
                           if(T_exSquitter.TC(i)==29)
                              TargetState(Q)=i;
                              Q=Q+1;
                           else
                              if(T_exSquitter.TC(i)==30)
                                 AircraftOperationStatus(U)=i;
                                 U=U+1;
                              end
                           end
                        end
```

```
                end
              end
            end
          end
        end
      end
    end
end
%Create a graphic of percentatge of each type message
figure (1)
x=[length(AircraftIdentification) length(SurfacePosition)
length(AirbornePositionBaro) length(AirborneVelocities)
length(AirbornePositionGNSS) length(Reserved) length(Reserved)
length(TargetState) length(AircraftOperationStatus)];
x=x/length(T_exSquitter.Message)*100;
bar(x)
title('Percentage of each type message');
xticklabels({'AircraftIdentification','SurfacePosition','AirbornePositionB','Airborne
Velocities','AirbornePositionG','Reserved','AircraftStatus','TargetState','AircraftO
perationStatus'});
ytickformat('percentage');
text(1:length(x),x,num2str(x'),'vert','bottom','horiz','center');

%Create table for each type message (9 types at total)
T_AircraftIdentification=T_exSquitter(AircraftIdentification,:);
T_SurfacePosition=T_exSquitter(SurfacePosition,:);
T_AirbornePositionBaro=T_exSquitter(AirbornePositionBaro,:);
T_AirborneVelocities=T_exSquitter(AirborneVelocities,:);
T_AirbornePositionGNSS=T_exSquitter(AirbornePositionGNSS,:);
T_Reserved=T_exSquitter(Reserved,:);
T_AircraftStatus=T_exSquitter(AircraftStatus,:);
T_Targetstate=T_exSquitter(TargetState,:);
T_AircraftOperationStatus=T_exSquitter(AircraftOperationStatus,:);

%% Plot altitude perfil of each aircraft
% plot the baro altitude
i=1;
j=1;
while(i<=height(T_AirbornePositionBaro))
    if isnan(T_AirbornePositionBaro.ICAO24(i))
        i=i+1;
    else
        ICAO24(j)=T_AirbornePositionBaro.ICAO24(i);
        j=j+1;
        i=i+1;
    end
end

ICAO24=unique(ICAO24);
```

```
i=1;
j=1;

for j=1:length(ICAO24)
    m=1;
    for i=1:length(T_AirbornePositionBaro.ICAO24)
        tf=isequal(T_AirbornePositionBaro.ICAO24(i),ICAO24(j));
        if (tf==1)
            positionVector(m)=i;
            m=m+1;
        end
    end
    figure (2)
    x=T_AirbornePositionBaro(positionVector,:).Altitude;
    y=T_AirbornePositionBaro(positionVector,:).Time;
    plot(y,x,'Marker','.','MarkerSize',10)
    hold on
    positionVector=[];
end
hold off
title('Altitude')
xlabel('Time')
ylabel('Altitude(foot)')

%% Plot altitude perfil of each aircraft
% plot the baro altitude
i=1;
j=1;
while(i<=height(T_AirbornePositionBaro))
    if isnan(T_AirbornePositionBaro.ICAO24(i))
        i=i+1;
    else
        ICAO24(j)=T_AirbornePositionBaro.ICAO24(i);
        j=j+1;
        i=i+1;
    end
end

ICAO24=unique(ICAO24);

i=1;
j=1;

for j=1:length(ICAO24)
    m=1;
    for i=1:length(T_AirbornePositionBaro.ICAO24)
        tf=isequal(T_AirbornePositionBaro.ICAO24(i),ICAO24(j));
        if (tf==1)
            positionVector(m)=i;
            m=m+1;
```

```
        end
    end
    figure (2)
    x=T_AirbornePositionBaro(positionVector,:).Altitude;
    y=T_AirbornePositionBaro(positionVector,:).Time;
    plot(y,x,'Marker','.','MarkerSize',10)
    hold on
    positionVector=[];
end
hold off
title('Altitude')
xlabel('Time')
ylabel('Altitude(foot)')




%% plot aircrafts route on the map
%Delete rows with CRC=1
toDelete=seal2.CRC==0;
Tcoded=seal2(toDelete,:);

%Aicrafts has position information
toDelete=~isnan(Tcoded.Latitude);
Tcodedposition=Tcoded(toDelete,:);
toDelete=Tcodedposition.Latitude~=0;
Tcodedposition=Tcodedposition(toDelete,:);

%create table of position for each aircraft
TypeAircraft=unique(Tcodedposition.ICAO24);
toDelete=~isnan(TypeAircraft);
TypeAircraft=TypeAircraft(toDelete,:);

for i=1:length(TypeAircraft)
     l=1;
     vector=[];
    for j=1:height(Tcodedposition)
        if(TypeAircraft(i)==Tcodedposition.ICAO24(j))
            vector(l)=j;
            l=l+1;
        end
    end
    TAircraft(i).lat=Tcodedposition(vector,:).Latitude;
    TAircraft(i).long=Tcodedposition(vector,:).Longitude;
end


for i=1:length(TypeAircraft)
```

```
    geoplot(TAircraft(i).lat,TAircraft(i).long,'Linewidth',2)
    hold on
    geoplot(TAircraft(i).lat(end),TAircraft(i).long(end),'Marker','x','MarkerSize',10)
    hold on
end
hold off
```

ANNEX 3

MATLAB code to receive signal:

```
% Request user input from the command-line for application parameters
userInput = helperAdsbUserInput;

% Calculate ADS-B system parameters based on the user input
[adsbParam,sigSrc] = helperAdsbConfig(userInput);

% Create the data viewer object and configure based on user input
viewer = helperAdsbViewer('LogFileName', userInput.LogFilename, ...
    'SignalSourceType', userInput.SignalSourceType);
if userInput.LogData
  startDataLog(viewer);
end
if userInput.LaunchMap
  startMapUpdate(viewer);
end

% Create message parser object
msgParser = helperAdsbRxMsgParser(adsbParam);

% Start the viewer and initialize radio time
start(viewer)
radioTime = 0;

% Main loop
i=1;
j=1;
Savemsg=struct('Header',{},'ICAO24',{},'TC',{},'AirborneVelocity',{},'Identification'
,{},'AirbornePosition',{});
while radioTime < userInput.Duration


     if adsbParam.isSourceRadio
        if adsbParam.isSourcePlutoSDR
            [rcv,~,lostFlag] = sigSrc();
        else
            [rcv,~,lost] = sigSrc();
            lostFlag = logical(lost);
        end
    else
        rcv = sigSrc();
        lostFlag = false;
     end

  % Process physical layer information (Physical Layer)
```

```
  [pkt,pktCnt] = helperAdsbRxPhy(rcv, radioTime, adsbParam);
  % Parse message bits (Message Parser)
  [msg,msgCnt] = msgParser(pkt,pktCnt);

  for l=1:length(msg)
      if(msg(l).Header.CRCError==0)
%           Savemsg(j)=savemessage(msg(l));
          Savemsg(j).Header=msg(l).Header;
          Savemsg(j).ICAO24=msg(l).ICAO24;
          Savemsg(j).TC=msg(l).TC;
          Savemsg(j).AirborneVelocity=msg(l).AirborneVelocity;
          Savemsg(j).Identification=msg(l).Identification;
          Savemsg(j).AirbornePosition=msg(l).AirbornePosition;
          j=j+1;
      end
  end

  % View results packet contents (Data Viewer)
  update(viewer, msg, msgCnt, lostFlag);
  % Save the signal received to plot
  Time(i)=radioTime;
  Data(1:length(rcv),i)=rcv;
  % Update radio time
  radioTime = radioTime + adsbParam.FrameDuration;
  i=i+1;
end
%% plot PPM
% (with previouly loaded signal when is needed)
fs=2.4e6;
x=real(rcv);
y=imag(rcv);
Time=0:0.0216/51840:0.0216-0.0216/51840;
figure (1)
plot(Time,x(1:length(Time)))
hold on
plot(Time,y(1:length(Time)))
hold off
title('Pulse Shaping');
xlabel('Time');
ylabel('Apmlitud');
% plot constellation of a signal
figure (2)
I=real(rcv);
Q=imag(rcv);
plot(I(1:200),Q(1:200));
xlabel('In-phase samples')
ylabel('Quadrature samples')

%Plot IQ samples
figure (3)
```

```
x=1:1:length(rxData);
plot(x,I,'r')
hold on
plot(x,Q,'b')
hold off
xlim([0 length(x)])
xlabel('Nº of samples');
ylabel('Amplitud');
legend('In-phase samples','Quadrature samples')

%spectrum plot
figure(4)
fs=2.4e6; %Mhz
y=fft(rcv);
n=length(rcv);
y0 = fftshift(y);        % shift y values
f0 = (-n/2:n/2-1)*(fs/n); % 0-centered frequency range
power0 = abs(y0).^2/n;    % 0-centered power
power0=pow2db(power0);
plot(f0,power0);
xlim([-fs/2 fs/2]);
xlabel('Frequency (Mhz)');
ylabel('Power(dB)');
% Stop the viewer and release the signal source
stop(viewer)
release(sigSrc)
```